AN ASSESSMENT OF THE BIT-ERROR-RATE PERFORMANCE OF QPSK, 8PSK, 8PSK/TCM AND GMSK VIA THE TRACKING AND DATA RELAY SATELLITE SYSTEM 650 MHZ-WIDE KA-BAND CHANNEL

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Abstract

In June 2000, NASA launched the first of three next generation Tracking and Data Relay Satellites (TDRS-H, I and J) that incorporate a 650 MHz-wide Ka-band Single Access Return (KaSAR) service using the 25.25 – 27.5 GHz space-to-space link (SSL) allocation. In parallel with this space segment upgrade, NASA has been upgrading the ground segment to support the 650 MHz-wide Ka-band service. As part of this upgrade effort, analyses were performed to determine the fidelity requirements of the ground terminal equipment and to estimate the implementation loss of the Tracking and Data Relay Satellite System (TDRSS) KaSAR 650 MHz service for customer data rates from 600 Mb/sec to 1.2 Gb/sec using various modulation schemes. This paper summarizes the results of the TDRSS KaSAR 650 MHz service implementation loss analysis.

1.0 Introduction

Modifications to the TDRSS ground segment to support a KaSAR 650 MHz service are being performed under the NASA Goddard Space Flight Center (GSFC) Ka-Band Transition Product (KaTP). In support of these modifications, simulation and analytical models were developed to determine appropriate fidelity requirements for the new hardware, evaluate vendor bids and hardware noncompliances, and estimate the total implementation loss of the TDRSS KaSAR 650 MHz service.

The simulation models were developed to incorporate the primary customer transmitter and TDRSS distortions including modulator gain and phase imbalance, phase noise, channel gain and group delay variation, amplifier nonlinearities, and spurs. The output of the models was Bit-Error-Rate (BER) performance versus Eb/No.

Using the models as well as hardware requirements and measurement data, a comprehensive assessment of the TDRSS KaSAR 650 MHz service implementation loss was performed. This assessment evaluated the performance of the service for a variety of modulation schemes including Offset Quadrature Phase Shift Keying (OQPSK), 8-ary Phase Shift Keying (8PSK), Trellis Coded 8-ary Phase Shift Keying (8PSK/TCM) and Gaussian Minimum Shift Keying (GMSK). The analysis focused on customer data rates between 800 Mb/sec and 1 Gb/sec, however, a range of 600 Mb/sec to 1.2 Gb/sec was analyzed.

2.0 Approach

2.1 Overview

TDRSS KaSAR 650 MHz service end-to-end link models were developed to simulate the performance of the customer spacecraft transmitter, the space-to-space link (SSL) between the customer spacecraft and TDRS H,I,J, the TDRS H, I, J spacecraft transponder, the space-to-ground link (SGL) between the TDRS H,I,J and the ground terminal, and the TDRSS ground terminal at NASA's White Sands Complex (WSC). A BER estimation capability was included in the models, and the output of the simulation was a BER versus Eb/No curve. The simulation models included as many distortions as possible, all of which were operator-configurable. Distortions which were simulated included data asymmetry, I/Q data skew, data rise time, gain imbalance, phase imbalance, bandlimiting, gain flatness, gain slope, phase nonlinearity (or group delay variation), AM/AM, AM/PM, spurious PM, spurious outputs, incidental AM and phase noise.

For some distortions, analytical techniques were used rather than simulation methods to determine their impact on TDRSS KaSAR 650 MHz service BER performance. Distortions which were addressed analytically included data bit jitter and frequency instability. For 8PSK, 8PSK/TCM and GMSK modulation schemes, gain imbalance, phase imbalance, I/Q data skew and data asymmetry were also addressed analytically.

The TDRSS KaSAR 650 MHz service total implementation loss (at a BER of 10^{-5}) was determined by adding the implementation loss amount obtained via simulation to the amount obtained via analytical methods. Since so few distortions were evaluated analytically, this direct summation of the simulation implementation loss component and the analytical implementation loss component provides an accurate assessment of total implementation loss.

2.2 Assumptions

This analysis included the following assumptions:

- An unlimited TDRSS SGL downlink Effective Isotropically Radiated Power (EIRP) was used in the analysis. This allowed the analysis to focus on the relative performances of the various modulation schemes and on the effects of TDRSS 650 MHz channel bandlimiting on high data rates. For reference purposes, the actual TDRSS SGL downlink EIRP is such that an SGL downlink C/No (at WSC) of about 113.7 dB-Hz can be expected.
- The customer transmitter distortion characteristics used in the simulation were equal to the maximum allowable values per preliminary TDRSS Ka-band customer transmitter constraint documentation [1]. Table 1 provides a summary of the customer transmitter distortion levels used in this analysis.
- The TDRS distortion characteristics for this analysis were based upon TDRS H measurement data. TDRS distortions included bandlimiting, gain flatness, gain slope, phase nonlinearity, AM/AM, AM/PM and phase noise. Figures 1 and 2 provide an overview of the TDRS gain flatness and phase nonlinearity used for this analysis (data based upon TDRS H measurement data but scaled to exactly meet specification limits; this ensures a conservative analysis for all TDRS H, I, J spacecraft and spacecraft configurations). Figures 3 and 4 provide an overview of the TDRS TWTA P_{out} vs P_{in} and φ_{out} vs P_{in} characteristics used for this analysis (TDRS H measurement data).
- The ground terminal distortion characteristics were equal to the required values specified in the *Ka-Band Transition Product System Requirements Document* [2] with the exception that no ground terminal spurs were simulated and the total ground terminal phase nonlinearity (including the correcting effects of the waveguide equalizer) was 30° peak-to-peak (based upon hardware developer estimates). Table 2 provides a summary of the ground terminal distortion levels used in this analysis. Figure 5 provides a plot of the two 30° peak-to-peak ground terminal phase nonlinearity shapes used

for this analysis (random shapes were used as no measurement data was available at the time of this analysis).

Table 1. Customer Transmitter Distortions

Parameter	Value(1)
3 dB Bandwidth, MHz	≥ 2x channel data rate
Roll-off, dB/MHz	5^{th} order Butterworth roll-off
Gain Flatness (p-to-p), dB	0.6 over ±230 MHz
Gain Slope, dB/MHz	0.1
Phase Nonlinearity (p-to-p), °	6.0 over ±230 MHz
AM/AM, dB/dB	0.47
AM/PM, °/dB	12.0
Data Rise Time, %	≈ 5
Incidental AM, %	5.0 @ 4.0 MHz(2)
Spurious PM, ° rms	2° rms @ 10 MHz(2)
Spurious Outputs, dBc	-30 dBc @ 40 MHz(2) -15 dBc @ 450 MHz(2)
Phase Noise, ° rms	1 Hz – 10 Hz: 27.2 10 Hz – 100 Hz: 13.6 100 Hz – 1 kHz: 3.6 1 kHz – 400 MHz: 2.0
Gain Imbalance, dB	0.25
Phase Imbalance, °	2.0
Frequency Stability	See Reference [1]
I/Q Data Skew, %	3
Data Asymmetry, %	3
Data Bit Jitter, %	0.1
Data Bit Jitter Rate, %	0.1

Notes:
1. Distortions simulated included 3 dB bandlimiting, roll-off, gain flatness, gain slope, phase nonlinearity, AM/AM, AM/PM, data rise time, incidental AM, spurious PM, spurious outputs, phase noise, gain imbalance, phase imbalance, I/Q data skew and data asymmetry. Distortions addressed analytically included frequency stability and data bit jitter. Exceptions to this include gain imbalance, phase imbalance, I/Q data skew and data asymmetry which were addressed analytically rather than via simulation for 8PSK, 8PSK/TCM and GMSK and phase noise which was addressed analytically rather than via simulation for QPSK.
2. Frequency arbitrarily selected.

Figure 1. TDRS S/C Channel Magnitude Response

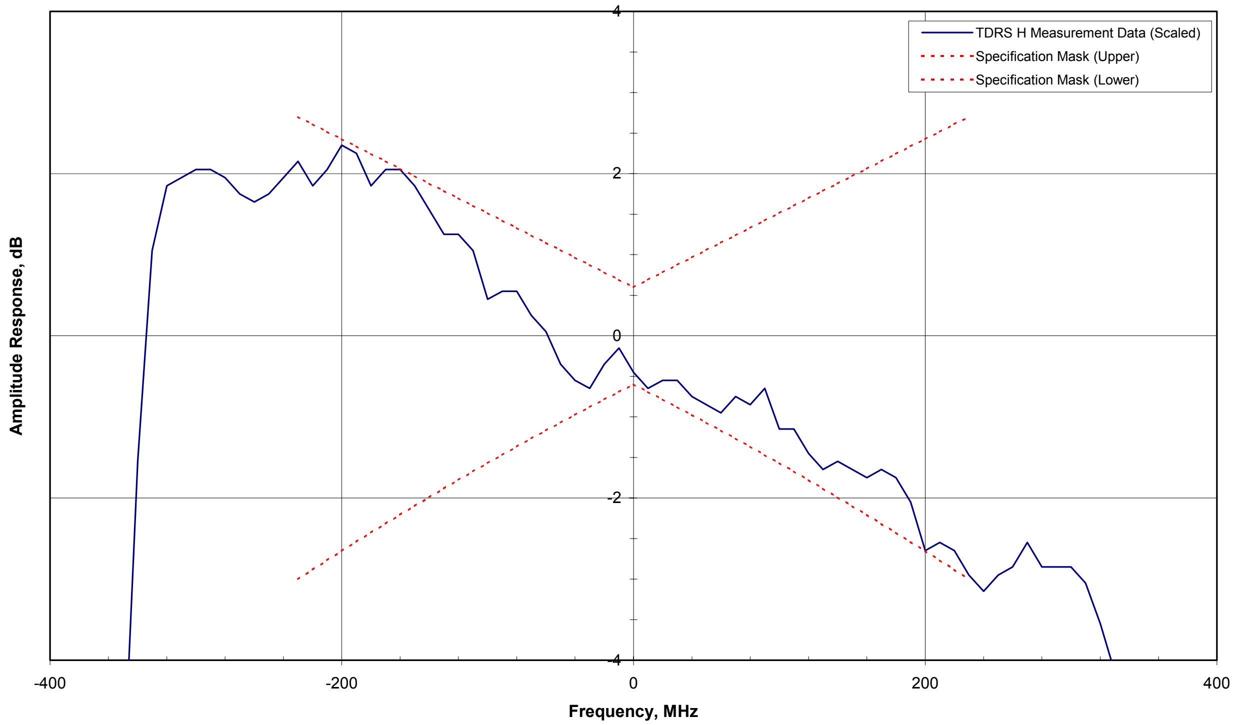


Figure 2. TDRS S/C Channel Phase Response (linear component removed)

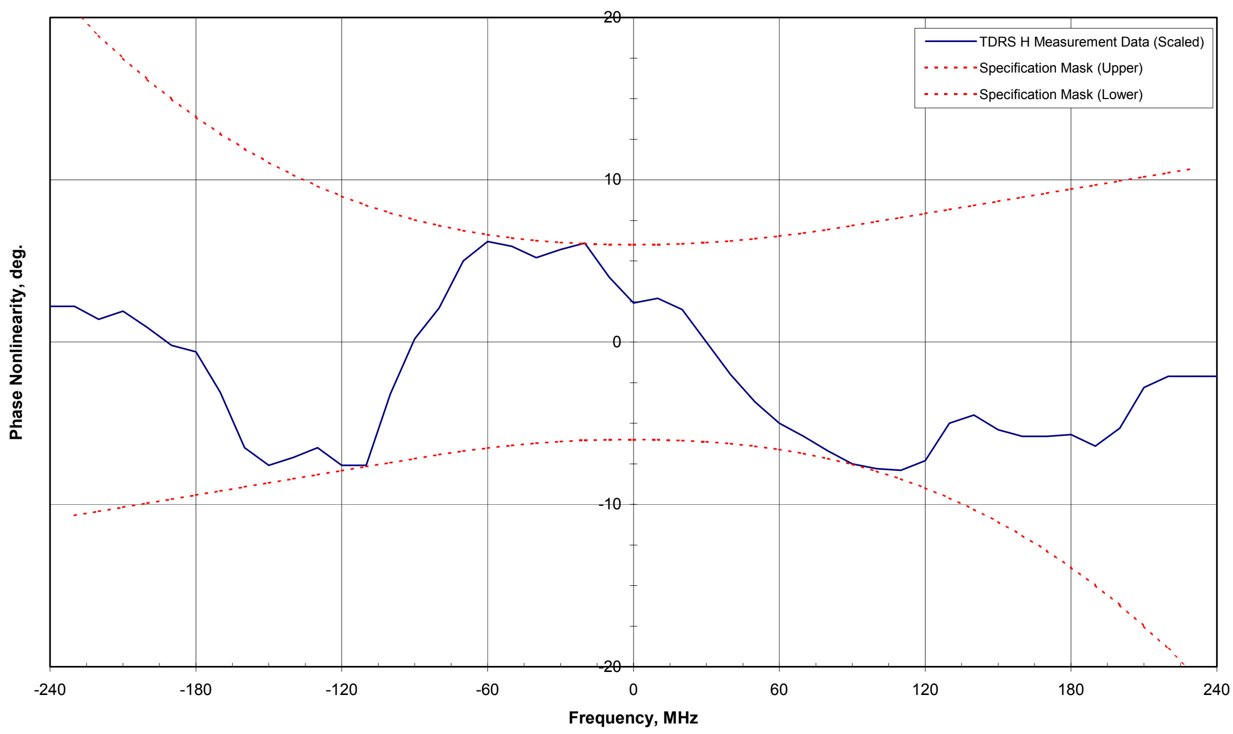


Figure 3. TDRS S/C P_{out} versus P_{in} Characteristics

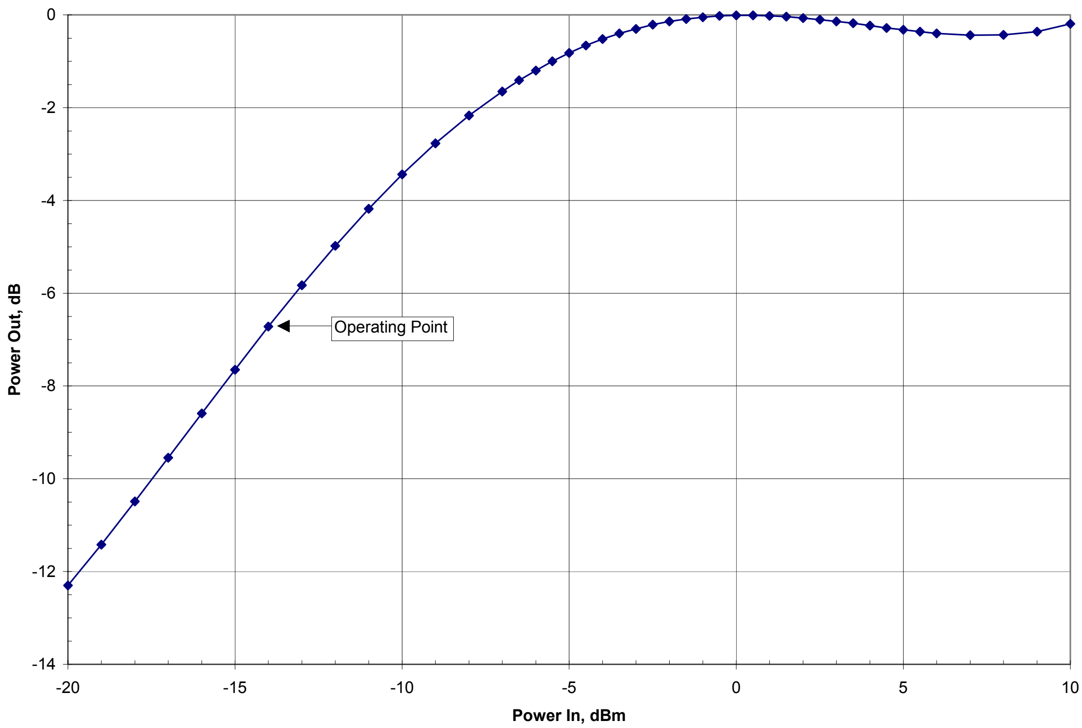


Figure 4. TDRS S/C φ_{out} versus P_{in} Characteristics

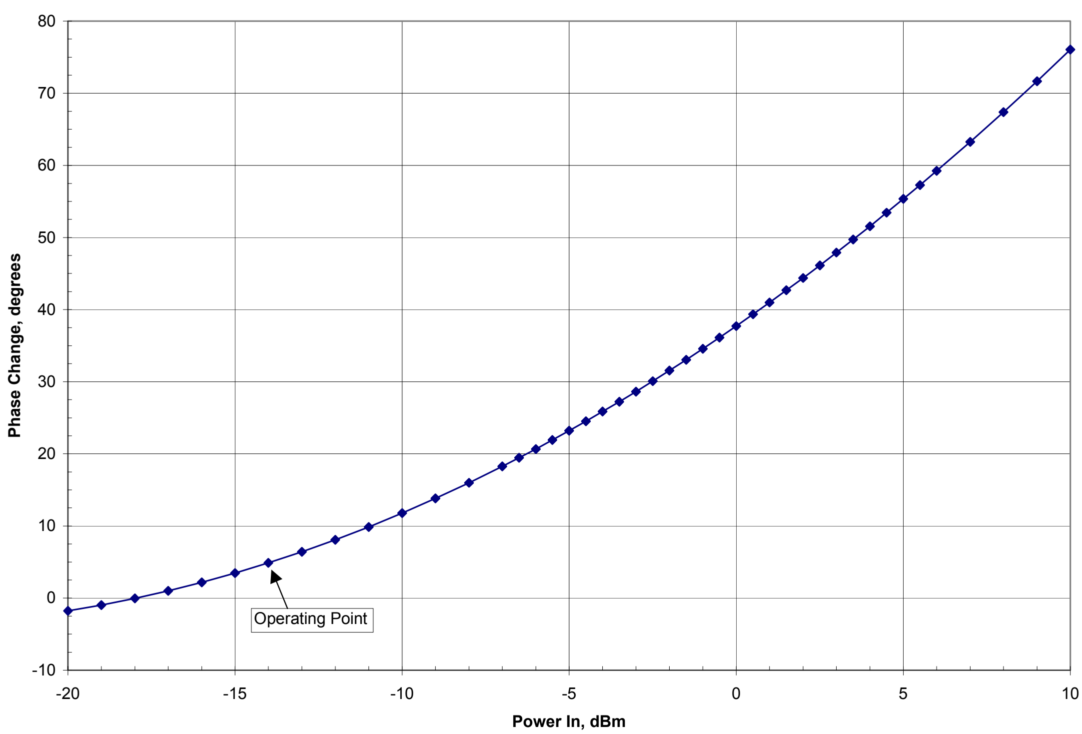
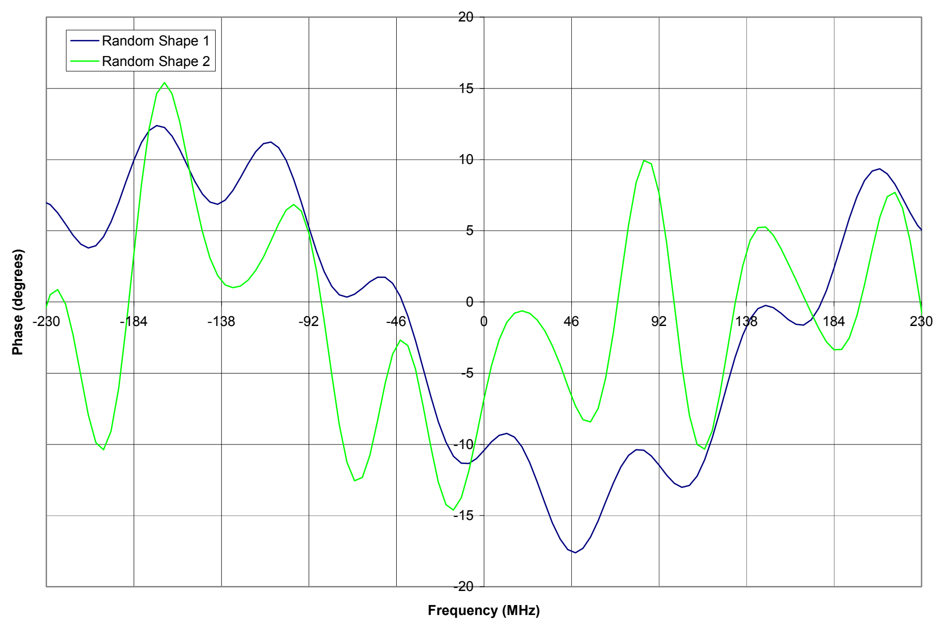


Table 2. Ground Terminal Distortion Settings

Parameter	Value
Bandwidth, MHz	650 (3 dB BW)
Roll-off, dB/MHz	6th order Butterworth roll-off
Gain Flatness (peak-to-peak), dB	1.2 over ±230 MHz
Gain Slope, dB/MHz	0.1
Phase Nonlinearity (peak-to-peak), °	30.0 over ±230 MHz
AM/AM, dB/dB	0.9
AM/PM, °/dB	1.0
Spurious Outputs, dBc	Not Simulated
Phase Noise, ° rms	1 Hz – 10 Hz: ≤1.4 10 Hz – 100 Hz: ≤1.4 100 Hz – 1 kHz: ≤2.7 1 kHz – 400 MHz: ≤1.0 (see notes 3 and 4)

Notes:
1. TDRS H, I, J Ground Segment includes the antenna and the Interfacility Link (IFL) equipment.
2. Ka-Band Infrastructure includes equipment just after the IFL equipment and up to the IF output (includes the waveguide equalizer and downconverter). Note that the ground terminal modifications provide KaSAR 650 MHz service support up to a 1.2 GHz IF. This analysis assumed receiver equipment after the 1.2 GHz IF so that a BER analysis could be performed.
3. Phase noise amounts selected prior to finalization of KaTP Specification [2].
4. In addition to this phase noise, additional phase noise due to the carrier tracking loop VCO was also simulated. This carrier tracking loop VCO phase noise contributed to the total untracked phase error an amount of 0.33° rms.

Figure 5. Ground Terminal Phase Nonlinearity Scenarios



2.3 Simulation Approach

The Signal Processing Worksystem (SPW) software was used to develop the TDRSS KaSAR 650 MHz service simulation models. Figure 6 provides a block diagram overview of the KaSAR 650 MHz service end-to-end link simulation model. Figure 7 provides an overview of the ground terminal simulation model assumed for this analysis.

Figure 6. TDRSS KaSAR 650 MHz Service End-to-End Link Simulation Model

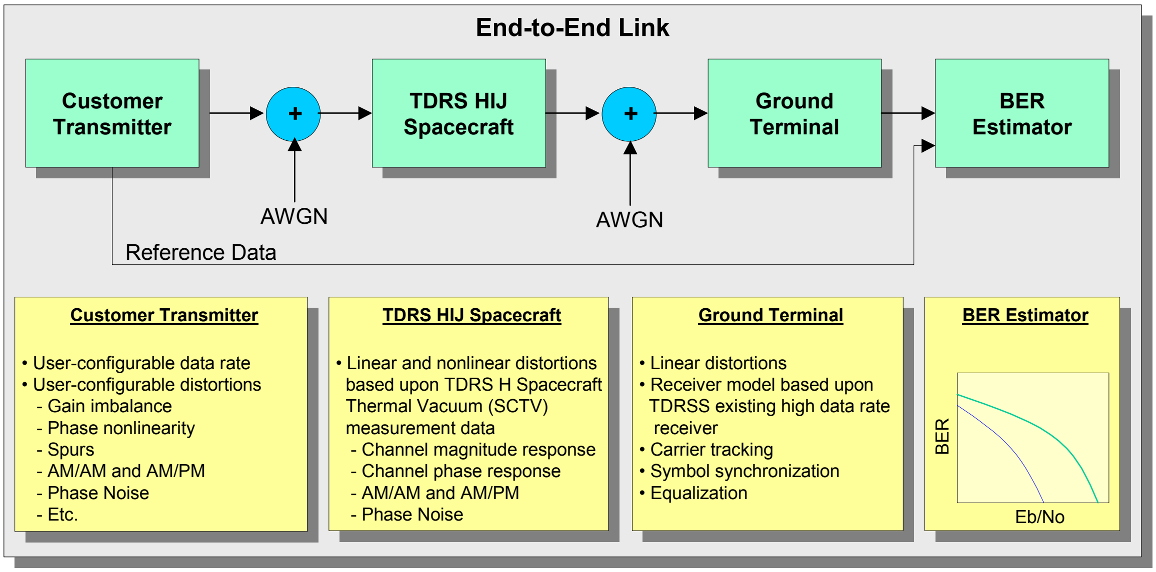
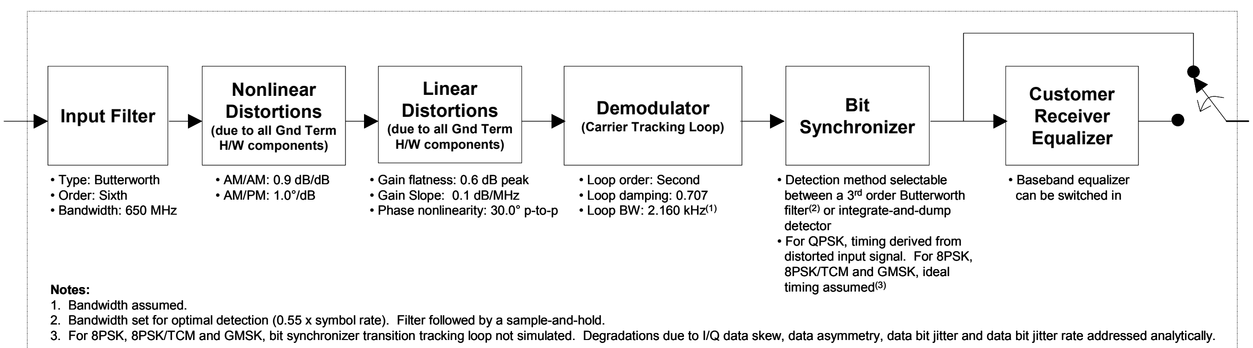


Figure 7. Ground Terminal Simulation Model



2.4 Analytical Approach

For some distortions analytical methods were used to determine the impact to BER. The methods used were based upon the material presented in the NASA/GSFC report titled *The Impact of TDRSS User Constraint Parameters on Bit Error Rate Performance* [3]. While the methods documented in Reference [3] are directly applicable to QPSK, they can be expanded upon or used as an approximation for GMSK, 8PSK and 8PSK/TCM.

The impact of an untracked phase error on QPSK was determined based upon material presented in the NASA/GSFC report titled *TDRSS and TDRS II Phase Noise Analysis Final Report* [4].

2.5 Approach Exceptions

A consistent analysis approach was used for each modulation scheme evaluated with the following exceptions:

- For the 8PSK, 8PSK/TCM and GMSK simulations, ideal timing was assumed for the data detectors (i.e., the bit synchronizer transition tracking loop was not simulated). For the QPSK simulations, data detector timing was derived from the incoming distorted signal (i.e., the bit synchronizer transition tracking loop was simulated). Simulation of the bit synchronizer transition tracking loop was not expected to impact the results appreciably (especially since bit jitter was addressed analytically). The bit synchronizer was not simulated in the 8PSK, 8PSK/TCM and GMSK simulations.
- The impact of phase noise on QPSK was determined analytically rather than via simulation as was used for 8PSK, 8PSK/TCM and GMSK. This approach was selected due to the large body of available reference material detailing the impact of an untracked phase error on QPSK, and the unusually long simulation runs required to accurately simulate phase noise.
- The impact of gain imbalance, phase imbalance, I/Q data skew and data asymmetry on 8PSK, 8PSK/TCM and GMSK was determined analytically rather than via simulation as was used for the QPSK portion of the analysis. This approach was selected to limit simulation model development.
- For the 8PSK, 8PSK/TCM and GMSK analysis, the customer transmitter nonlinear characteristics were based upon actual TWTA measurement data, whereas, for the QPSK analysis, the customer transmitter nonlinear characteristics were based upon equations which always produced the specified amount of AM/AM and AM/PM regardless of the P_{in}. This approach was selected to more accurately model the impact of an actual transmitter TWTA.

3.0 Results

Table 3 summarizes the TDRSS KaSAR 650 MHz service implementation loss estimates for various modulation schemes, service configurations, hardware configurations and distortion scenarios. Results are presented for 4- and 8-state 8PSK/TCM, 8PSK, GMSK and QPSK modulation schemes with service data rates ranging from 600 Mb/sec to 1.2 Gb/sec. Results are presented for two data detection methods, an Integrate-and-Dump (I/D) and a 3rd order Butterworth filter with a sample-and-hold. Baseband equalization performed by the customer receiver equipment is assumed for selected analysis scenarios.

Assuming the customer modulation is 8PSK/TCM and baseband equalization is used in the receiver equipment, the TDRSS KaSAR 650 MHz channel should be able to support data rates in excess of 1 Gb/sec with a reasonable implementation loss. The 8PSK/TCM modulation scheme is resilient to the distortions and bandlimiting of the TDRSS KaSAR 650 MHz channel due to the coding which is included in the modulation. As would be expected, results of Table 3 indicate the more states in the TCM decoding process, the better the BER performance. From the results, it is not fully clear which detection approach yielded the superior results, however, it could be argued that I/D's would not be feasible for the data rates discussed in this paper.

Assuming the customer modulation is QPSK, the TDRSS KaSAR 650 MHz channel should be able to support data rates up to about 800 Mb/sec with a reasonable implementation loss. The original design goal of the TDRSS KaSAR 650 MHz-wide channel was to support data rates up to 800 Mb/sec assuming QPSK modulation, and this goal appears to have been achieved.

Table 3. Summary of Expected Implementation Loss Amounts for Various TDRSS KaSAR 650 MHz Service Scenarios[1]

Communication Scenario		Ground Terminal Description			Total Implementation Loss[2, 3, 4]
Modulation/ Coding	Data Rate	Phase Nonlin Shape	Detection Method	Customer End Equalizer	
8PSK/TCM (4-state)	800 Mb/sec	Random 1	Butterworth Filter[5]	No	2.94 dB
	800 Mb/sec	Random 1	Butterworth Filter[5]	Yes	2.00 dB
	800 Mb/sec	Random 2	Butterworth Filter[5]	No	2.76 dB
	800 Mb/sec	Random 1	Integrate-and-Dump	No	2.55 dB
	800 Mb/sec	Random 2	Integrate-and-Dump	No	2.70 dB
	850 Mb/sec	Random 1	Butterworth Filter[5]	No	5.33 dB
	900 Mb/sec	Random 1	Butterworth Filter[5]	No	7.78 dB
	1 Gb/sec	Random 1	Butterworth Filter[5]	No	> 10 dB
	1 Gb/sec	Random 1	Butterworth Filter[5]	Yes	2.93 dB
	1 Gb/sec	Random 2	Butterworth Filter[5]	No	7.31 dB
	1 Gb/sec	Random 1	Integrate-and-Dump	No	9.19 dB
	1 Gb/sec	Random 2	Integrate-and-Dump	No	6.67 dB
	1.2 Gb/sec	Random 1	Butterworth Filter[5]	Yes	3.70 dB
8PSK/TCM (8-state)	800 Mb/sec	Random 1	Butterworth Filter[5]	No	2.69 dB
	800 Mb/sec	Random 1	Butterworth Filter[5]	Yes	1.60 dB
	1 Gb/sec	Random 1	Butterworth Filter[5]	No	≈ 8.00 dB
	1 Gb/sec	Random 1	Butterworth Filter[5]	Yes	2.82 dB
8PSK Uncoded	800 Mb/sec	Random 1	Integrate-and-Dump	No	>> 10 dB
	800 Mb/sec	Random 1	Butterworth Filter[5]	Yes	5.91 dB
	800 Mb/sec	Random 2	Integrate-and-Dump	No	>> 10 dB
QPSK Uncoded	600 Mb/sec	Random 1	Butterworth Filter[5]	No	3.53 dB
	600 Mb/sec	Random 1	Butterworth Filter[5]	Yes	2.36 dB
	800 Mb/sec	Random 1	Butterworth Filter[5]	No	4.95 dB
	800 Mb/sec	Random 1	Butterworth Filter[5]	Yes	2.30 dB
	800 Mb/sec	Random 2	Butterworth Filter[5]	No	4.45 dB
	800 Mb/sec	Random 2	Butterworth Filter[5]	Yes	3.05 dB
GMSK (BT_b = 0.5)	800 Mb/sec	Random 1	Butterworth Filter[5]	No	4.19 dB
	800 Mb/sec	Random 2	Butterworth Filter[5]	No	6.36 dB

Notes:
1. See Section 2 of this paper for a complete description of the analysis approach including exact distortion parameter settings and hardware configuration parameters.
2. At 10^{-5} BER and relative to the theoretical performance of the particular modulation scheme being analyzed. QPSK theoretical BER performance crosses 10^{-5} BER at Eb/No = 9.6 dB. 8PSK theoretical BER performance crosses 10^{-5} BER at Eb/No = 13.18 dB. 8PSK/TCM (monodimensional) theoretical BER performance crosses 10^{-5} BER at Eb/No = 7.12 dB for 4 states and 6.82 for 8 states. GMSK (BT_b = 0.5) theoretical BER performance crosses 10^{-5} BER at Eb/No ≈ 10.4 dB.
3. Values determined using a combination of analytical and simulation methods. For 8PSK, 8PSK/TCM and GMSK, all distortions simulated with the exception of customer gain imbalance, phase imbalance, I/Q data skew, data asymmetry, data bit jitter and frequency instability which were addressed analytically. For QPSK, all distortions simulated with the exception of customer data bit jitter, customer frequency instability and system phase noise which were addressed analytically.
4. For 800 Mb/sec 8PSK/TCM, the 95% confidence interval is approximately ±0.25 dB. For 1 Gb/sec 8PSK/TCM, the 95% confidence interval is approximately ±0.45 dB. For GMSK, the 95% confidence interval is approximately ±0.3 dB.
5. Third order Butterworth filter of bandwidth 0.55 x symbol rate. A sample-and-hold was used after the filter.

Although 8PSK provides a higher bits/Hz amount than QPSK, 8PSK/TCM and GMSK, its use for very high data rate KaSAR 650 MHz service does not appear to be feasible due to the high implementation loss amounts expected.

It should be noted that the results of Table 3 are based upon two widely-used, but generic detection methods. Neither method would likely be optimal for the TDRSS KaSAR 650 MHz channel. If a more optimal data detection method was assumed, the results of Table 3 would improve.

4.0 Conclusions

The TDRSS KaSAR 650 MHz-wide channel should be capable of supporting customer data rates in excess of 1 Gb/sec assuming the customer modulation is 8PSK/TCM and the receiver performs baseband equalization. If the customer modulation is QPSK or GMSK, the TDRSS KaSAR 650 MHz-wide channel should be capable of supporting customer data rates in excess of 800 Mb/sec assuming the receiver performs baseband equalization. If the customer modulation is 8PSK, the TDRSS KaSAR 650 MHz-wide channel can support high data rate service, however, the implementation loss may be prohibitively high.

This study concludes that 8PSK/TCM modulation with baseband equalization in the receiver will yield the best performance from an implementation loss point-of-view.

5.0 References

[1] *TDRSS Ka-Band User Constraint Specifications*, SES-450-100027, John Wesdock, et al, ITT Industries, 7 August 2000.

[2] *Ka-Band Transition Product (KaTP) System Requirements Document (SRD)*, 450-SRD-KaTP, NASA/GSFC, March 2002.

[3] *The Impact of TDRSS User Constraint Parameters on Bit Error Rate Performance*, STI/E-TR-7017, Richard S. Orr and Leonard Schuchman/STel, 7 October 1977.

[4] *TDRSS and TDRS II Phase Noise Analysis Final Report*, TR93077, Matt Griffin, John Wesdock, et al., Stanford Telecomm, 30 September 1993.